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14. ABSTRACT

Development of the new structured materials which have a frequency band where both the electromagnetic permittivity (e) and the magnetic permeability (m) are negative. These new materials are now known as Left-Handed Metamaterials (LHM), and had the remarkable prediction in 1962 by Prof. V. Veselago (then in the USSR) that they would exhibit a negative index of refraction.

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Progress Report for AFOSR Grant F49620-00-1-0380
Sheldon Schultz, Principal Investigator

We wish to first thank our AFOSR Program Officer and his supervisor for their great help in rapidly providing the referenced award based on our bringing to their attention our development of the new structured materials which have a frequency band where both the electromagnetic permittivity (e) and the magnetic permeability (μ) are negative. These new materials are now known as Left-Handed Metamaterials (LHM), and had the remarkable prediction in 1962 by Prof. V. Veselago (then the USSR) that they would exhibit a negative index of refraction.

The two papers listed as publications, (copies enclosed) confirmed that:

(1) we could design and fabricate a (reasonably) isotropic 2-D structure with the confirmed left-handed band in both the frequency-wavevector diagram obtained by numerical simulations, and also in the actual fabricated sample as tested in our special "2-D" X-band microwave test chamber. APL 78, 489 (2001) reprint enclosed, and

(2) once we had an isotropic 2-D material, we could perform a classic Snell's Law experiment using a prism shaped sample of our 2-D LHM, and show that whereas a teflon callibration sample produced the usual expected bending of the microwaves (both in magnitude and direction), the LHM sample truly was refracted to the other side of the normal to the surface, as predicted for a negative index of refraction. Science 292, 77, 2001) reprint enclosed.

It is hard for us to discuss these results further, except to say that speaking for myself (and not for my collaborators), I regard this paper and result as the most dramatic and important in my 41 years at UCSD !

Much remains to be done, true theoretical issues, further numerical simulations, new material designs, and of course further confirming experiments of each advance. We plan to continue in this new exciting field of research in our future funding.

To: Weinstock Harold Civ AFRL/AFOSR <harold.weinstock@afosr.af.mil>
From: Shelly Schultz <sschultz@ucsd.edu>
Subject: Copy of my (late) Progress Report
Cc: pylesNicki
Bcc:
X-Attachments:

Dear Harold,

I enclose below the regrettable delayed Progress Report (from the corresponding Final Report) that was for the first "one shot" funding you kindly arranged for us.

I went over to the Physics Business in panic when I received some overdue notices, and they said I should send this to you, while they incorporate the other papers in the Official Final Report. If there is anything else I could do that would help you at this point, please let me know.

Have a good Seder.

Shelly

Progress Report for AFOSR Grant F49620-00-1-0380:

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Microwave transmission through a two-dimensional, isotropic, left-handed metamaterial

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We present experimental data, numerical simulations, and analytical transfer-matrix calculations for a two-dimensionally isotropic, left-handed metamaterial (LHM) at *X*-band microwave frequencies. A LHM is one that has a frequency band with simultaneously negative $\varepsilon_{\mathrm{eff}}(\omega)$ and $\mu_{\mathrm{eff}}(\omega)$, thereby having real values of index of refraction and wave vectors, and exhibiting extended wave propagation over that band. Our physical demonstration of a two-dimensional isotropic LHM will now permit experiments to verify some of the explicit predictions of reversed electromagnetic-wave properties including negative index of refraction as analyzed by Veselago [Usp. Fiz. Nauk **92**, 517 (1964), Sov. Phys. Usp. **10**, 509 (1968)].
[DOI: 10.1063/1.1343489]

Recently, Smith *et al.*[1] demonstrated a left-handed metamaterial (LHM), and discussed the relationship of this material to the theoretical predictions of Veselago.[2] Veselago predicted that materials with simultaneous negative effective permittivity $\varepsilon_{\mathrm{eff}}(\omega)$ and negative effective permeability $\mu_{\mathrm{eff}}(\omega)$ have unusual reversed electromagnetic-wave propagation phenomena. Since the initial report[1] was based on a physical construction of elements which exhibited left-handed propagation for only one dimension (i.e., one direction of incidence and polarization), there remained a critical need to develop and verify that higher-dimensional LHMs could readily be made, so as to provide realistic model systems for confirming the expected reversals of Snell's law, the Doppler shift, and Cherenkov radiation.[2] Here, we provide an experimental demonstration and numerical confirmation that we have now made a two-dimensional (2D) LHM suitable for further experiments that will illustrate some of the predicted reversed electromagnetic properties.

Electromagnetic waves will only propagate in a medium that has a real index of refraction, $n_{\mathrm{eff}}(\omega)=\sqrt{\varepsilon_{\mathrm{eff}}(\omega)\mu_{\mathrm{eff}}(\omega)}$. If either $\varepsilon_{\mathrm{eff}}(\omega)$ or $\mu_{\mathrm{eff}}(\omega)$ is negative, then $n_{\mathrm{eff}}(\omega)$ is imaginary, and there will be no transmission through a thick sample. If, however, both $\varepsilon_{\mathrm{eff}}(\omega)$ and $\mu_{\mathrm{eff}}(\omega)$ are less than zero, electromagnetic waves will propagate through the medium, but the negative root must be chosen for $n_{\mathrm{eff}}(\omega)$,[3] and the group and phase velocities will be antiparallel.[2]

The initial transmission experiments by Smith *et al.*[1] were performed on a one-dimensional (1D) LHM that consisted of an array of unit cells, each cell consisting of one split-ring resonator (SRR), as discussed by Pendry *et al.*,[4] and one conducting post. The composite displayed an anisotropic left-handed transmission band from 4.70 to 5.15 GHz. These previous experiments were carried out in a 2D scattering chamber described in detail in Ref. 5. As the scattering chamber was originally designed for *X*-band microwave frequencies (8–12 GHz), we have now changed the design parameters of our material to result in a LHM at *X* band, and we are thus able to use *X*-band waveguide components to couple to the 2D scattering chamber. This allows us to utilize plane-wave incident and transmitted waves, which can be compared more easily to the numerical simulations.

We scaled our transmission band to *X*-band frequencies by reducing the overall dimensions of the SRRs and achieved 2D isotropy by placing the SRRs along two orthogonal axes in a lattice. To further ease the burden of fabrication, the negative permittivity medium has been introduced as wire strips mounted behind the SRRs. Since the wire strips are much thinner than the posts used in the previous work, it was necessary to increase the density of the wire strips to two per unit cell to achieve similar negative values of the permittivity.

Using a shadow mask/etching technique, we fabricated printed circuit boards with SRRs on one side and wire strips on the other. Figure 1(a) shows a diagram of a single SRR of the type we used for these experiments. The boards were cut and assembled such that each unit cell has six SRRs and two wire strips arranged as shown in Fig. 1(b). The printed circuit board material is 0.25 mm G10 fiberglass and the SRRs and wire strips are 0.03-mm-thick copper. The dielectric

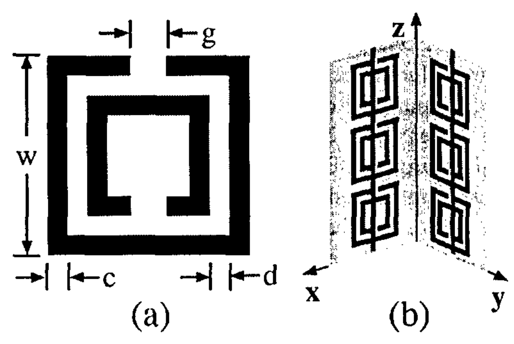

FIG. 1. (a) Diagram of a single split-ring resonator (SRR), $c=0.25$ mm, $d=0.30$ mm, $g=0.46$ mm, $w=2.62$ mm, and the SRR is square. (b) Each unit cell has six copper SRRs and two wire strips on thin fiberglass boards. The wire strips are 1 cm long, centered on the SRRs, and on the opposite side of the board from the SRRs. The angle between the fiberglass boards is 90° to make square unit cells with a lattice constant of 5.0 mm.

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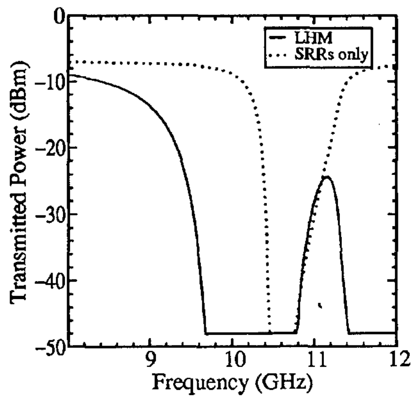

FIG. 5. Transfer-matrix calculation results for the LHM and "SRR only" material.

tivity function[8] as in Eq. (2), thereby reducing the region of negative permittivity to occupy a band between the resonant frequency ω_{e0} and the plasma frequency ω_{ep}.

The general form of the transmission curves can be compared with a 1D transfer-matrix calculation, assuming the forms in Eqs. (1) and (2) for the material parameters. The results of this calculation, which utilized the method outlined in Ref. 5, are shown in Fig. 5. The following values were used: $f_{mp}=11.0\,\text{GHz}$, $f_{m0}=10.5\,\text{GHz}$, $f_{ep}=20\,\text{GHz}$, $f_{e0}=10\,\text{GHz}$, and $\gamma=1$ GHz. The length of the 1D slab was 15 cm. No attempt was made to actually fit the transfer-matrix results to the measured data to derive exact values for the parameters. There is, however, qualitative agreement between the measured and calculated transmitted power curves. Note that the gap due to the negative permeability appears to occur at lower frequency than the transmission band when the negative permittivity is added. This feature is related to the finite size of the structure; the region of negative permeability actually extends to higher frequency, but the associated attenuation length in the material increases such that more power is transmitted through the structure. To match the measured attenuation of the propagation band we set $\gamma=1$ GHz, suggesting this structure has relatively large losses.

The agreement between the transfer-matrix calculation and the measured transmittance through the LHM indicates that it is appropriate to treat the LHM as a homogeneous material with frequency-dispersive material parameters. This reduction in complexity is essential to the further interpretation of the LHM concept.

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